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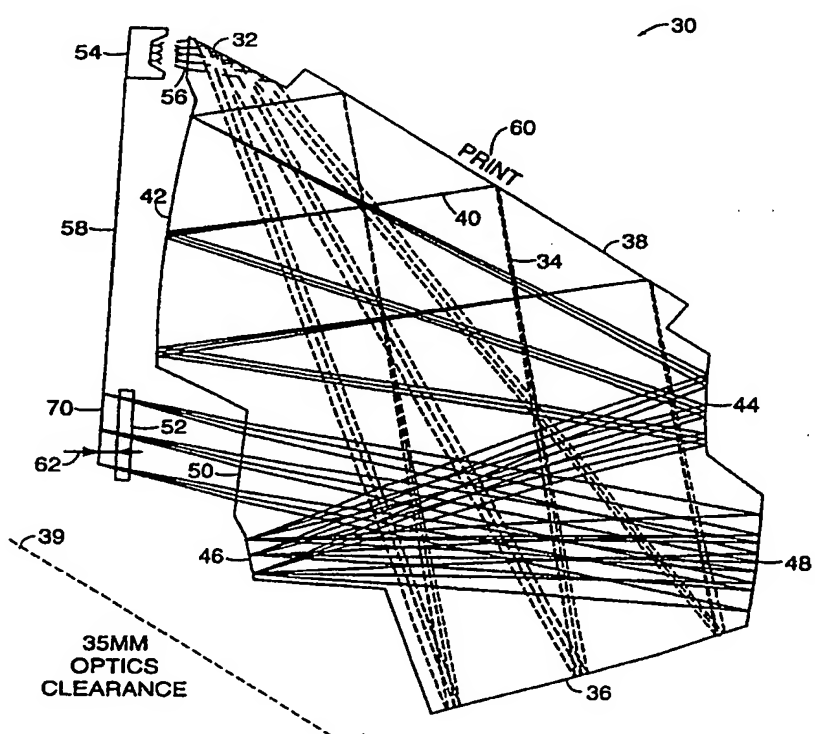
(54) Title: OPTICAL FINGERPRINT READER

(57) Abstract

An optical fingerprint reader wherein a volume of solid material with a plurality of surfaces defines an illumination path and an imaging path. Light from a source travels along the illumination path, and an image of an object is transmitted by the imaging path. The illumination path is defined by an optical subsystem that includes as one of the plurality of surfaces, a stop at which a focused image of the light source appears. The imaging path is a subset of the illumination path and is defined by a finite conjugate afocal optical subsystem that focuses an image of the object onto a detector. In addition, the stop simultaneously performs dual functions. For the illumination path, the stop becomes a field stop by controlling image illumination. For the imaging path, the stop becomes a field stop by limiting the angular field of illumination for the image of a print at an optical detector.



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OPTICAL FINGERPRINT READER

Technical Field

This invention relates to a system for detecting fingerprints, and more particularly, a volume of solid material that includes a finite conjugate afocal optical subsystem for imaging a print, and an optical subsystem that supplies uniform illumination to a fingerprint receiving surface and an optical detector.

Background Information

Whether in high or low technology environments, inexpensive and reliable security systems are required. A primary link in the security chain is to accurately identify a limited number of users with the requisite security clearance. As is well known, each person carries an identifier that is inextricably linked to that individual. Those identifying characteristics or biometric measurements may be obtained by observation, from photographs, facial topography, genetic or biological markers, retinal scans, fingerprints, hand geometry, voice recognition, or by using low tech options like dental records to identify a particular individual. While the aforementioned techniques are useful, some are impractical for certain environments, some techniques require expensive equipment and complicated chemical analyses before results can be obtained, and still others are simply unreliable.

However, human fingerprints are the least invasive biometric measurement and may be obtained easily without complex chemical analyses, and are reliable identifiers. Furthermore, with the advent of computers, the fingerprint may be analyzed using an off-the-shelf software matching scheme and a result produced rapidly. In the area of security systems, it is generally accepted that no two individuals have the same fingerprint. Accordingly, using a fingerprint as an identifier is a reasonable alternative.

In recent years obtaining an optical fingerprint reader composed of a plastic has been difficult. A primary reason for the difficulty obtains from the fact that plastic shrinks. The shrinking changes the optical characteristics of the device and impacts the quality of the image at an optical detector. Furthermore, because of the poor quality of the image of the print, the results obtained from a computer driven matching sequence may produce erroneous results.

Summary of the Invention

The disclosed invention relates to an optical fingerprint reader that includes a unitary volume of solid material made of a plastic acrylic that is insensitive to the shrinking that occurs in other systems. The optical fingerprint reader uses mirrors and two refractive surfaces (one as an entrance window and the other as a powered exit window) to obtain an image of a fingerprint.

To improve the quality of the fingerprint image, the optical fingerprint reader has an illumination path for the light source and an imaging path for the image of the print. In addition, a physical stop at the center focus within the volume of solid material controls the illumination, the location, and the quality of the image of the print. The optical fingerprint reader operates in a range where the volume of solid material is transparent to at least visible light. Also, the volume of solid material has a dimension of no more than 35 millimeters between a print receiving surface and a line parallel to the print receiving surface (i.e., the optics clearance is 35 millimeters or less). Therefore, the optical fingerprint reader of the invention is a compact, inexpensive solution that provides high resolution imaging of a fingerprint.

The optical fingerprint reader may be used as an integral component to a general security system, or to obviate the need for using passwords to a computer terminal. The optical fingerprint reader may be used in conjunction with automobiles, smart cards, passport identification cards, driver's licenses, electronic commercial transactions, automated teller machines, or any system which requires a technique for identifying a person and verifying that the person is who they purport to be, while occupying a minimum amount of time and space.

In general, one aspect of the invention relates to an optical system that includes a volume of solid material with a plurality of surfaces that define both an illumination path and an imaging path. Light from a source travels along the illumination path, and an image of an object is created by the imaging path. In addition, the disclosed invention includes a stop as one of the plurality of surfaces that is both an aperture stop for the imaging path and a field stop for the illumination path.

The illumination path is defined by an optical subsystem that includes the stop at which a focused image of the light source appears. In the illumination path, the stop

behaves like a field stop by limiting the angular field of illumination that occurs in the image backplane. The imaging path is defined by a finite conjugate afocal optical subsystem for focusing an image of the object onto a detector. The imaging path includes a subset of the optical surfaces in the illumination path which also includes the stop. However, for the imaging path, the stop behaves like an aperture stop by controlling image illumination and reducing aberrations in the image backplane.

Embodiments of this aspect of the invention can include nine optical surfaces as the core optics: three flat surfaces, three conic mirrors, and three anamorphic aspheres (AAS). The three flat surfaces can be one transmitting, one reflecting, and a fingerprint platen which works by frustrated total internal reflection (TIR). The three conic mirrors can be two parabolic and one hyperbolic The three anamorphic aspheres (AAS) can be two reflectors and one transmitter.

The foregoing and other objects, aspects, features, and advantages of the invention will become more apparent from the following description and from the claims.

Brief Description of the Drawings

In the drawings, like reference characters generally refer to the same parts throughout the different views. Also, the drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention.

FIG. 1 is a perspective view of the optical fingerprint reader according to the invention.

FIG. 2 is a schematic diagram of the internal volume of the optical fingerprint reader showing the plurality of surfaces and the accompanying reflections.

FIG. 3 is an unfolded diagram in the form of a paraxial ray trace of an illumination path of the optical fingerprint reader of FIGS. 1 and 2.

FIG. 4 is an unfolded diagram in the form of a paraxial ray trace of an imaging path of the optical fingerprint reader of FIGS. 1 and 2.

Description

The invention relates to an optical system for reading fingerprints. The optical system has a volume of solid material which can receive a print. The volume includes a plurality of surfaces which define both an illumination path and an imaging path. The illumination path is for light from a light source, and the imaging path is for creating an image of the print. The disclosed invention also includes a stop that simultaneously provides dual functions. In the illumination path, the stop becomes a field stop that limits the angular spread of the field of illumination in the image backplane, and in the imaging path, the stop becomes an aperture stop that limits the size of the axial cone of energy reflected from the print.

The illumination path is defined by an optical subsystem that includes a field stop as one of the plurality of surfaces. A focused image of the light source appears at the field stop which, as described below, enhances detection capabilities. The imaging path is defined by a finite conjugate afocal optical subsystem that includes a stop and focuses the image of the print onto a detector.

The optical system includes the volume of solid material which includes the plurality of surfaces. The surfaces can include a receiving surface, a first reflecting surface, a second reflecting surface, a stop, a third reflecting surface, and a refracting surface.

In one embodiment, the receiving surface is a platen used for receiving a print. The receiving surface is uniformly illuminated by light from the light source. The first reflecting surface within the volume of solid material is for receiving an optical image of the print from the receiving surface and converging the image of the print. In addition, the first reflecting surface receives collimated light from the receiving surface and converges the light. A second reflecting surface is for receiving the image of the print from the first reflecting surface and diverging that image. Also, the second reflecting surface receives the light from the first reflecting surface and converges the light.

The stop receives the image of the print from the second reflecting surface and diverges the image. The stop also receives the light from the light source in focus, and then diverges the light. In addition, the stop is located at the center focus meaning that the principal rays are nearly collimated in object and image space, which insures that magnification is stable with focus shift, that distortion is low, and that the angle of incidence on the total internal reflection object space is the same for all object points and can be as low as permitted to achieve total internal reflection.

A third reflecting surface receives the image of the print from the stop and converges the image. The third reflecting surface also receives the light from the stop and collimates the light for illuminating an optical detector. The final interface encountered by the light rays inside of the volume of solid material is the refracting surface. The refracting surface receives the image of the print from the third reflecting surface and focuses the image onto a detector. The refracting surface also receives light from the third reflecting surface and collimates the light which uniformly illuminates the detector.

Sign and Coordinate Conventions

In conventional optical usage, light travels from left to right, so that positive distances are to the right and negative distances are to the left. The optical axis is usually denoted as the z-axis. The y-z plane is the plane of all drawings, and is defined as the meridional plane for the system. The x-axis is perpendicular to the meridional plane.

Convention dictates that the sign of the thicknesses, defined as the distance from any surface to the next surface measured along the optical axis, is reversed by a reflection. That is, when a ray traveling from left to right encounters a mirror, the ray is reversed and travels from right to left. For the optical fingerprint reader, the light paths are folded for compactness, and the reflections are at various angles to the optical axis.

In addition, convention dictates that curvatures, defined as the reciprocal of the radius of curvature, and radii of curvature are positive when they are convex toward the left, i.e., when the center of curvature is to the right, and negative when the curvatures are concave towards the left. However, in the present description, the radii of curvature is positive when the incoming ray encounters a convex surface (center of curvature to the right), and the radii of curvature is negative when the incoming ray approaches a concave surface (center of curvature to the left).

Optical Reflections Within The System

Referring to FIG. 1, a perspective view of an embodiment of an optical fingerprint reader 10 is shown. The optical fingerprint reader 10 is an optical system for imaging a print 60. As shown in FIG. 1, the optical fingerprint reader 10 is a unitary volume of solid material on which a receiving surface 38 or platen is used for receiving a print 60. In the disclosed embodiment, the optical fingerprint reader 10 includes a light source 54 (not shown), an optical detector 70, and a

plurality of surfaces disposed between the light source 54 and the optical detector 70. The plurality of surfaces define both an illumination path 34 for light from the light source 54, and an imaging path 40 for an image of the print 60.

The plurality of surfaces according to the invention includes a receiving surface 38 for receiving a print 60, a stop 46 (not shown) for receiving a focused image of the light source 54 and for reflecting the focused image of the light source 54. The plurality of surfaces further include a refracting surface 50 for transmitting collimated light from the light source 54 to an optical detector 70 and for focusing the image of the print 60 onto an optical detector 70.

In more detail and referring to FIG. 2, the optical fingerprint reader 10 includes a volume of solid material 30 having a plurality of reflecting surfaces. In one embodiment, the volume of solid material 30 is composed of a plastic. The volume of solid material 30 that lies between the print 60 and the optical detector 70 is less than or equal to about 35 millimeters in a direction that is perpendicular to the receiving surface 38. That is, the distance between the receiving surface 38 and a dashed line 39 that is parallel to the receiving surface 38 is less than or equal to 35 millimeters. The plastic can be an acrylic such as methyl methacrylate. In addition, one or more of the reflecting surfaces of the volume of solid material 30 can have one or more coatings to create the internal reflections required to image a print 60.

In one embodiment of the invention, the volume of solid material 30 is plastic such as an acrylic material like polymethyl methacrylate ($n = 1.49$). Whatever the type of material selected for the volume of solid material 30, a light source 54 with appropriate illumination characteristics is selected. Specifically, the light emitted by the light source 54 should be at such a wavelength or range of wavelengths that the volume of solid material 30 is transparent to the emitted light. In the disclosed embodiment, the light source 54 is an LED that emits light at approximately 534 nanometers, and the volume of solid material 30 is transparent to at least visible light.

The plurality of surfaces within the volume of solid material 30 define both an illumination path 34 for light from a light source 54 and an imaging path 40 for imaging the print 60. The illumination path 34 is shown as a dashed line, and the imaging path 40 which is a subset of the illumination path 34 is shown as a solid line within the volume of solid material 30. The following is a description of the optical reflections and refractions that occur first for the light illumination path 34 and then for the print imaging path 40.

The Illumination Path

Still referring to FIG. 2, the light source 54 (a light emitting diode LED) is positioned on a backplane 58. The light emanating from the LED 54 is coupled through a flat surface 56 of the volume of solid material 30. The flat surface 56 is hereinafter referred to as an entrance window and has a radius of curvature equal to infinity. Because of a change in indices of refraction as light passes from the LED 54 and through the entrance window 56, the light from the LED 54 is both refracted and reflected at the entrance window 56. As a result, some light is coupled into the volume of solid material 30 and a portion is reflected backwards. By introducing an index matching fluid or lens between the LED 54 and the entrance window 56, the light coupled into the volume of solid material 30 may be increased.

Alternatively, the LED 54 may also be included within the volume of solid material 30, and in doing so, the number of interfaces between the light source 54 and the volume of solid material 30 is reduced, and the amount of light available for imaging a print 60 deposited on a receiving surface 38 may be enhanced. In another embodiment of the invention, the entrance window 56 may be defined by a stop with a one millimeter diameter and a relative aperture f/2, where the f-number is inversely proportional to the numerical aperture. As is well known, the numerical aperture is the index of refraction times the sine of the half angle of the cone of illumination and is an element which determines the amount of light coupled into the volume of solid material 30. In addition, an LED 54 with a small active area relative to the diameter of the entrance window 56 may also be considered.

Light from the entrance window 56 is transmitted through the volume of solid material 30 to a flat folding mirror 32 where the light undergoes a reflection. The flat folding mirror 32 is positioned at approximately 60 degrees relative to the entrance window 56. Light reflected from the flat folding mirror 32 propagates towards a collimating surface 36. The collimating surface 36 is shaped as a concave paraboloid of revolution.

In one embodiment of the invention, the radius of curvature for the collimating surface 36 is $R = -101.6$ mm. Recall that convention requires that curvatures (defined as the reciprocal of the radius of curvature) and radii of curvature are positive when they are convex toward the left (i.e., when the center of curvature is to the right), and negative when the curvatures are concave towards the right (i.e., when the center of curvature is to the left). However, in this case, the radii of curvature is positive when the incoming ray encounters a convex surface (center of curvature

to the right), and the radii of curvature is negative when the incoming ray approaches a concave surface (center of curvature to the left).

The collimating surface 36 is a parabolic reflector that collimates the light received from the flat folding mirror 32 via the light source 54. The collimating surface 36 is a concave parabolic reflector that uniformly illuminates a receiving surface 38, which receives the print 60, with parallel light. In the disclosed embodiment, the receiving surface 38 is a flat surface or platen located opposite the collimating surface 36. The receiving surface 38 with the print 60 deposited thereon is uniformly illuminated by parallel light from the collimating surface 36.

With the print 60 deposited on the receiving surface 38, as described below, a portion of the light is transmitted out of the volume of solid material 30 or is scattered through the ridges of the print 60, while another portion of the light is internally reflected by the valleys of the print 60. The print 60 is imaged by the internally reflected light from the receiving surface 38. However, if no print 60 is deposited on the receiving surface 38, each ray of light will undergo total internal reflection (TIR) at the receiving surface 38.

From the receiving surface 38, the light is further reflected onto a first reflecting surface 42. The first reflecting surface 42 is a concave paraboloid reflector for receiving the collimated light from the receiving surface 38. The first reflecting surface 42 has a radius of curvature $R = -80$ mm, and is used to converge the light onto a second reflecting surface 44. The second reflecting surface 44 is the convex portion of a hyperboloid reflector with a radius of curvature $R = 27$ mm. The second reflecting surface 44 may be used to converge the illuminating light to a focal point located on a stop 46. For the illumination path 34, the stop 46 is a surface that limits the angular field of the print 60 in the image backplane 58. As a result, the stop 46 becomes a field stop for the illumination path 34, and as described below, the stop 46 becomes an aperture stop for the imaging path 40.

The illumination level is controlled because an enlarged image of the LED 54 is formed on the stop 46, and then projected onto an image backplane 58 while the uniformity of the image of the print 60 is improved by reducing optical aberrations. By placing the stop 46 on a mirrored surface, the illumination level and uniformity of the illumination are controlled. In addition, because the stop 46 has power and asphericity, image location and image quality of the print 60 are also controlled.

In addition, the stop 46 is located at the center focus meaning that the principal rays are nearly collimated in object and image space, which insures that magnification is stable with focus shift, distortion is low, and that the angle of incidence on the total internal reflection object space is the same for all object points and can be as low as permitted to achieve total internal reflection.

The surface of the stop 46, which receives the focused light from the second reflecting surface 44, is shaped as an anamorphic asphere. The stop 46 has a radius of curvature in the y-direction Ry = – 101.96236 mm, and a radius of curvature in the x-direction Rx = – 223.01901 mm. As is well known, an anamorphic aspheric surface is characterized by a power or magnification that depends on direction. More specifically, the anamorphic surface has a power or magnification that is different in the x-direction than in the y-direction. The variation in magnification provided by the anamorphic surface introduces an additional degree of freedom in the invention by allowing control of the image location and image quality.

The stop 46 is also a mirrored surface used to diverge the light received from the second reflecting surface 44, towards a third reflecting surface 48. The third reflecting surface 48 is an anamorphic asphere where the y profile is paraboloid with a conic constant k = – 1.0. The radius of curvature for the third reflecting surface 48 in the y-direction is Ry = – 71.94639 mm, and the radius of curvature in the x-direction is Rx = – 58.67734 mm. The third reflecting surface 48 collimates the light, i.e., bends the light parallel, and sends the light towards the refracting surface 50. At the refracting surface 50, the light exits the volume of solid material 30, and illuminates an optical detector 70. The refracting surface 50 is an anamorphic asphere with a radius of curvature in the y-direction Ry = –209.33426 mm, and a radius of curvature in the x-direction Rx = –37.33902 mm.

In one embodiment of the invention, the image is collected by a charge coupled device (CCD) located on the image backplane 58. The CCD image sensor is preceded by a flat CCD window 52. The flat CCD window 52 is approximately 0.801 mm thick as measured from the central vertex of the plate, and is placed at a separation distance 62 of approximately 0.960 mm from an optical detector 70. In general, the flat CCD window 52 is a passive surface which provides protection for the optical detector 70. However, in one embodiment of the invention, the flat CCD window 52 may have a curved surface to provide field flattening, distortion correction, or made of an optical filtering glass for spectrally filtering light from the light source 54. In the disclosed embodiment, the image sensor or optical detector 70, may have an active

area of 3.59 mm x 4.79 mm with 492(x) x 512(y) pixels, a 230 millivolt sensitivity at f1.6 and 3200K, a 62 dB dynamic range, and a peak sensitivity at 530 nm.

The light illumination path 34 is summarized in FIG. 3. Figure 3 is an unfolded diagram in the form of a paraxial ray trace 64 of the light illumination path 34 in the fingerprint optical reader 10, and more specifically through the volume of solid material 30. The paraxial ray trace 64 is a first order approximation of the optical interactions within the volume of solid material 30 as light from the LED 54 is reflected from the various surfaces discussed above.

Referring to FIG. 3, the paraxial ray trace 64 represents light from LED 54 diverging through the entrance window 56′ (not shown) and from the flat folding mirror 32′ (not shown) towards the collimating surface 36′. The collimating surface 36′ bends the light parallel towards the receiving surface 38′. The parallel light from the receiving surface 38′ is converged by the first reflecting surface 42′ and is again converged by the second reflecting surface 44′ to a focus point located on the stop 46′. The light diverges from the stop 46′, and is collimated by the third reflecting surface 48′ which directs the light through the refracting surface 50 and onto the image backplane 58′. In addition, the stop 46′ behaves like a field stop by controlling the angular field of illumination at the image backplane 58 for the light illumination path 34. Also, note that from the paraxial ray trace 64, the finite conjugate afocal optical subsystem of the imaging path 40 may be identified as a subset of the light illumination path 34.

An afocal system is generally defined as an optical system without a focal length or a system in which both the object and image are located at infinity. In addition, such a system is characterized by having a fixed magnification independent of object distances, and a range of object distances yielding real images that is severely restricted. In an embodiment of the disclosed invention and referring to FIG. 3, an afocal optical subsystem is created by surfaces 38′-50′. The subsystem supplies the illumination that reaches an optical detector 70 located on the image backplane 58. Note that the light from the LED 54 is collimated and passes through the afocal optical subsystem parallel (effectively from infinity) and leaves the afocal optical subsystem parallel (effectively focused at infinity) through the refracting surface 50′ and onto the image backplane 58 where an optical detector 70 (not shown) is located.

The Imaging Path

Generally, afocal optics are used to image objects at infinite distances. However, in the present invention, the print 60 is located on the receiving surface 38 and at a finite distance from the image plane. Also, the object distance of the print 60 may vary by either depositing the print 60 directly onto the receiving surface 38 of the volume of solid material 30, or by introducing a material disposed between the receiving surface 38 and the print 60. Therefore, the object distance may vary, however, the image distance will remain essentially unchanged. Therefore, a conjugate relationship exists between the object of the print 60 located at the receiving surface 38, and an image plane located at an optical detector 70 positioned on a backplane 58. That is, the object distance of the print 60 may change while the image distance to an optical detector 70 effectively remains invariant. As a result, the optical interactions involving the image of the print 60 within the volume of solid material 30, as detailed below, describe a finite conjugate afocal optical subsystem.

Having described the illumination path 34, the imaging path 40 will now be described. Referring to FIG. 2, the imaging path 40 begins with an object being deposited onto the receiving surface 38. In the disclosed embodiment, the object deposited is a fingerprint or print 60. A print 60 may be deposited onto the volume of solid material 30 by depressing a human digit directly onto an external surface of the volume of solid material 30. The external surface is the receiving surface 38, and in one embodiment of the invention, the receiving surface 38 is a flat surface or platen.

In general, by depressing a human digit onto a surface, an oil based residue may be transferred directly to that surface. By using minimal force, a human digit may be depressed onto the receiving surface 38 simultaneously leaving behind an oil based residue atop the receiving surface 38. The oil based residue may have a patterned series ridges that form peaks and valleys. The peaks and valleys form the basis of the print 60 that is unique to each individual. In one embodiment of the invention, the receiving surface 38 includes a layer of urethane material disposed between the receiving surface 38 on which a print 60 may be placed.

As discussed above, light from an LED 54 is reflected from a collimating surface 36 towards the receiving surface 38. At the receiving surface 38, light may either be totally internally reflected, or a portion of the light may be reflected, and another portion is either scattered or

coupled outside the volume of solid material 30. When a print 60 is not deposited on the receiving surface 38, the light rays received from the collimating surface 36 will each be totally internally reflected. However, when a print 60 is deposited on the receiving surface 38, the oil from the print 60 creates a change in the index of refraction at the interface of the receiving surface 38 and an area external to the volume of solid material 30. The change in the index of refraction at that interface frustrates the total internal reflection, and a portion of the light is reflected while another portion of the light is scattered or coupled outside the volume of solid material 30.

The light reflected back into the volume of solid material 30 includes the image of the print 60 deposited on the receiving surface 38. The image of the print 60 transmitted through the volume of solid material 30 is a negative of the print 60 deposited on the receiving surface 38. The image of the print 60 consists of alternating light and dark regions where the dark regions represent the light that is either scattered or refracted out of the volume of solid material 30, and the light regions represent the light reflected back into the volume of solid material 30. The light regions also represent areas where the print 60 did not contact the receiving surface 38 and the oil based residue was not transferred to the receiving surface 38. Accordingly, light was reflected back into the volume of solid material 30 at those regions.

In contrast, the dark regions represent areas where the print 60 made contact with the receiving surface 38, and the oil based residue was transferred to the receiving surface 38. Because of a change in the indices of refraction at those interfaces, light was either coupled out or scattered from the volume of solid material 30. As a result, light and dark regions occur in the image of the print 60 that propagates through the volume of solid material 30 and towards an optical detector 70 located in the image backplane 58.

The first reflecting surface 42 is an off-axis paraboloid of revolution for receiving an optical image of the print 60 from the receiving surface 38, and for diverging the image of the print 60. The image of the print 60 is directed towards a second reflecting surface 44. The second reflecting surface 44 is used for receiving the image of the print 60 from the first reflecting surface and for diverging the image towards a stop 46. In the disclosed embodiment, the stop 46 is a surface within the volume of solid material 30 that limits the size of the image by only reflecting the light that covers the diameter of that surface.

The stop 46 is a physical stop that simultaneously performs dual functions by limiting the resolution of the image of the print 60 for the imaging path 40, and by limiting the amount of light propagating along the illumination path 34. As a result, the stop 46 behaves like an aperture stop for the imaging path 40 by limiting the size of the axial cone of energy from the print 60, and becomes a field stop for the illumination path 34 by limiting the angular field of illumination in the image backplane 58.

The stop 46 diverges the image of the print 60 towards a third reflecting surface 48. The third reflecting surface 48 is a concave anamorphic asphere used to converge the image of the print 60. The third reflecting surface 48 reflects the image of the print 60 onto a refracting surface 50 shaped as a convex anamorphic asphere. The refracting surface 50 further converges the image of the print 60. The combination of these two anamorphic surfaces, specifically, the third reflecting surface 48 and the refracting surface 50, allows the image of the print 60 to be focused onto an optical detector 70 located at the image backplane 58.

In addition, the refracting surface 50 is a weak anamorphic asphere that in combination with the third reflecting surface 48 corrects the anamorphic magnification characteristic of a finite conjugate afocal image of a tilted surface. In one embodiment of the invention, the weak anamorphic refractive surface 50 may be spherical or plano depending upon the tolerances required for image quality and anamorphic magnification. Furthermore, the image quality at the optical detector 70 is enhanced because the image forming beams in the volume of solid material 30 are small when compared to the diameter of the powered surfaces. Specifically, the image of the print 60 that is transmitted throughout the volume of solid material 30 is not larger than a few millimeters in diameter on each of the larger powered surfaces. As a result, sensitivity to surface irregularities from the manufacturing process is minimized.

The imaging path 40 is summarized in FIG. 4. Figure 4 is an unfolded diagram in the form of a paraxial ray trace 66 showing the imaging path 40 in the fingerprint optical reader 10. More specifically, the paraxial view is a ray trace of the path of the image of a print 60 through the volume of solid material 30. The paraxial ray trace 66 is a first order approximation of the optical interactions within the volume of solid material 30 as the image of the print 60 is reflected from the various surfaces discussed above.

The image paraxial ray trace 66 begins at the receiving surface 38″ where a print 60 is deposited and imaged by parallel light reflected from the collimating surface 36. The paraxial ray

trace 66 shows that the image of the print 60 diverges from the receiving surface 38″, and is reflected towards the first reflecting surface 42″. At the first reflecting surface 42″, the concave paraboloid of revolution further diverges the image of the print 60. In contrast to the light from the LED 54, the image of the print 60 at the stop 46″ diverges and is not focused. The stop 46″ may be a physical stop for the image of the print 60 because the diameter of this surface limits the size of the image transmitted through the volume of solid material 30.

The paraxial ray trace 66 shows the image of the print 60 directed towards the third reflecting surface 48″. The third reflecting surface 48″ is an anamorphic asphere that strongly converges the image of the print 60 onto another anamorphic aspheric surface. The refracting surface 50″ is a weak anamorphic asphere that focuses the image of the print 60 onto an optical detector 70 located on the image backplane 58″. In the disclosed embodiment, the refracting surface 50″ transmits the image of the print 60 through a flat CCD window 52″ towards an optical detector 70 located on the image backplane 58″.

Surface Characteristics

The surfaces of the volume of solid material 30 include three flat surfaces, three anamorphic aspheres, and three conic sections. The three flat surfaces are the entrance window 56, the flat folding mirror 32, and the receiving surface 38. Each is defined by a radius of curvature equal to infinity. The surfaces shaped as conic sections are the first reflecting surface 42 which is a paraboloid of revolution, the collimating surface 36 which is also a paraboloid of revolution, and the second reflecting surface 44 is a hyperboloid of revolution. In general, the conic sections are defined by the following equation

(1)
$$z = \frac{ch^2}{1+\sqrt{1-(1+k)c^2h^2}} + Ah^4 + Bh^6 + Ch^8 + Dh^{10} + Eh^{12} + Fh^{14} + Gh^{16} + Hh^{18} + Jh^{20}$$

where z is the sag of the surface parallel to the z-axis, c is the curvature at the pole of the surface , k is the conic coefficient for a paraboloid $k = -1$ and for a hyperboloid $k < -1$, $h^2 = x^2 + y^2$, and A, B, C, D, E, F, G, H, J are the fourth, sixth, eighth, tenth, twelfth, fourteenth, eighteenth and twentieth order deformations respectively. Note that $A = B = C = D = E = F = G = H = J = 0$ for a pure conic section.

The three surfaces shaped as anamorphic aspheres (AAS) are the stop 46, the third reflecting surface 48, and the refracting surface 50. As is well known in the art, an anamorphic asphere is a surface with bi-lateral symmetry in both the x and y direction which does not necessarily have rotational symmetry. In general, the AAS is described by the following equation:

$$(2) \qquad Z = \frac{CUX \cdot x^2 + CUY \cdot y^2}{1 + \sqrt{1 - (1+KX)CUX^2 - (1+KY)CUY^2 \cdot y^2}}$$
$$+ AR\{(1-AP)x^2 + (1+AP)y^2\}^2 + BR\{(1-BP)x^2 + (1+BP)y^2\}^3$$
$$+ CR\{(1-CP)x^2 + (1+CP)y^2\}^4 + DR\{(1-DP)x^2 + (1+DP)y^2\}^5$$

where Z is the sag of the surface parallel to the z-axis; CUX and CUY are the curvatures in the x and y directions respectively; KX and KY are the conic coefficients in x and y, respectively; AR, BR, CR and DR are the rotationally symmetric portions of the fourth, sixth, eighth and tenth order deformation from the conic; and AP, DP, CP and DP represent the non-rotationally symmetric components of the fourth, sixth, eighth, and tenth order deformation from the conic. This equation reduces to the aspheric type when CUX = CUY, KX = KY, and AP = BP = CP = DP = 0.

In one embodiment of the invention, the stop 46 has a radius of curvature in the y-direction of Ry = −101.96236 mm, and a radius of curvature in the x-direction of Rx = −223.01901 mm. The curvature, CUX and CUY in equation (2), is the inverse of the radius of curvature Rx and Ry. In another embodiment of the invention, the stop 46 is an anamorphic asphere with toroidal symmetry. A toroidal surface is a type of anamorphic asphere where one axis is cylindrical, and the other axis has a conic constant. Specifically, the other axis of the toroidal surface is not cylindrical.

As previously mentioned, light travels from left to right, so that positive distances are to the right and negative distances are to the left. Convention dictates that the sign of the thicknesses, defined as the distance from any surface to the next surface measured along the optical axis, is reversed by a reflection. That is, when a ray traveling from left to right encounters a mirror, the ray is reversed and travels from right to left and the sign is switched. For the optical fingerprint reader 10, the light paths are folded for compactness, and the reflections are at various

angles to the optical axis. Because of the sign conventions, the multiple reflections correspond to varying sign changes for measured distances and thicknesses.

Accordingly, the prescription table, Table I, contains a listing of the values for the core surfaces that form an embodiment of the optical fingerprint reader 10, and for clarity, Table I lists the absolute magnitude of the thicknesses for each surface. Table I also contains information regarding the surfaces used, and the corresponding radii of curvature for each surface that forms the structure of the volume of solid material 30 which is the framework for the optical fingerprint reader 10.

Using Table I, the preceding discussion, and an off-the-shelf software package like Code V™, the required surfaces for the optical fingerprint reader 10 and the volume of solid material 30 may be obtained.

Reference Number	Radius (mm)	Thickness (mm)	Comment
54		2.128910	LED Light Source
56	∞	2.080600	Flat Entrance Window
32	∞	43.152700	Flat Folding Mirror
36	-101.600	34.340000	Concave Paraboloid Reflector, k = 1.0
38	∞	22.00000	Flat Receiving Surface
42	-80.000	31.00000	Concave Paraboloid, Reflector, k = -1.0
44	27.00000	27.00000	Convex Hyperboloid, Reflector, k = -4.0
46	Ry = -101.96236 Rx = -223.01901	30.00000	Concave Toroid Reflector
48	Ry = -71.94639 Rx = -58.67734	31.000000	Concave Anamorphic Aspheric Reflector Where The Y Profile is Paraboloid, k = -1.0
50	Ry = -209.33426 Rx = -37.33902	6.000000	Convex Toroid Refractor
52	∞	0.801000	Flat CCD Window
62		0.960000	Separation Distance
58			Image Backplane

Table I: A prescription table listing the various surface specifications for an embodiment of the optical fingerprint reader. The relevant surfaces and their corresponding shapes, radius of curvature, and absolute magnitude of each surface thickness is shown.

Variations, modifications, and other implementations of what is described herein will occur to those of ordinary skill in the art without departing from the spirit and the scope of the invention as claimed. Accordingly, the invention is to be defined not by the preceding illustrative description but instead by the spirit and scope of the following claims.

What is claimed is:

Claims

1. An optical system, comprising:

a volume of material comprising a plurality of surfaces, the plurality of surfaces defining both an illumination path and an imaging path, the illumination path being for light from a light source, the imaging path being for an image of an object, the illumination path comprising an optical subsystem that includes as one of the plurality of surfaces a stop at which appears a focused image of the light source, the imaging path comprising a finite conjugate afocal optical subsystem that also includes the stop, the finite conjugate afocal optical subsystem for focusing the image of the object onto a detector.

2. The optical system of claim 1 wherein the illumination path further comprises:

as another one of the plurality of surfaces, a collimator for receiving light from the light source, collimating it, and providing the collimated light to the afocal optical subsystem.

3. The optical system of claim 2 wherein the collimator comprises a paraboloid of revolution.

4. The optical system of claim 1 wherein the stop comprises an anamorphic asphere.

5. The optical system of claim 1 wherein the afocal optical subsystem further includes:

as another one of the plurality of surfaces, a receiving surface for receiving the object; and

as still another one of the plurality of surfaces, a refractive surface for providing collimated light to the detector.

6. The optical system of claim 5 wherein the finite conjugate afocal optical subsystem further includes:

the receiving surface at which the image of the object originates; and

the refractive surface for focusing the image of the object onto the detector.

7. The optical system of claim 6 wherein the receiving surface includes a layer of urethane material disposed between the receiving surface and the object.

8. The optical system of claim 1 wherein the volume of material is transparent to at least visible light.

9. The optical system of claim 8 wherein the volume of material is transparent to at least a wavelength of about 534 nanometers.

10. The optical system of claim 1 wherein the volume of material comprises a plastic.

11. The optical system of claim 10 wherein the plastic comprises an acrylic.

12. The optical system of claim 11 wherein the acrylic comprises methyl methacrylate.

13. The optical system of claim 1 wherein the volume of material that lies between the object and the focused image of the object is less than or equal to about 35 millimeters in a direction that is perpendicular to the object..

14. The optical system of claim 1 wherein the imaging path is for the image of the object, and the object comprises a print.

15. An optical system for imaging a print, comprising:

a source of light;

a detector; and

a plurality of surfaces disposed between the source and the detector, the plurality of surfaces defining both an illumination path for light from the source and an imaging path for an image of the print, the plurality of surfaces comprising a receiving surface for receiving the print, a stop for receiving a focused image of the source and for reflecting the focused image of the source, and a refracting surface for providing collimated light from the source to the detector and for focusing the image of the print onto the detector.

16. The optical system of claim 15 wherein the stop comprises an anamorphic asphere.

17. The optical system of claim 15 wherein the receiving surface includes a layer of urethane material disposed between the receiving surface and the print.

18. The optical system of claim 15 wherein the plurality of surfaces are surfaces of a volume of material.

19. The optical system of claim 18 wherein the volume of material is transparent to at least visible light.

20. The optical system of claim 19 wherein the volume of material is transparent to at least a wavelength of about 534 nanometers.

21. The optical system of claim 18 wherein the volume of material comprises a plastic.

22. The optical system of claim 21 wherein the plastic comprises an acrylic.

23. The optical system of claim 22 wherein the acrylic comprises methyl methacrylate.

24. The optical system of claim 18 wherein the volume of material that lies between the object and the focused image of the object is less than or equal to about 35 millimeters in a direction that is perpendicular to the receiving surface.

25. The optical system of claim 15 wherein the print comprises a fingerprint.

26. An optical system for imaging prints, comprising:

a volume of material comprising a plurality of surfaces, the plurality of surfaces comprising:

a receiving surface for receiving a print and for being uniformly illuminated by collimated light;

a first reflecting surface for receiving an optical image of the print from the receiving surface and diverging the image, and for receiving the collimated light from the receiving surface and converging the light;

a second reflecting surface for receiving the image from the first reflecting surface and diverging the image, and for receiving the light from the first reflecting surface and converging the light;

a stop for receiving the image from the second reflecting surface and diverging the image, and for receiving the light in focus and diverging the light;

a third reflecting surface for receiving the image from the stop and converging the image, and for receiving the light from the stop and collimating the light; and

a refracting surface for receiving the image from the third reflecting surface and converging the image into focus, and for receiving the light from the third reflecting surface and collimating the light.

27. The optical system of claim 26 wherein the plurality of surfaces further comprise a collimator for providing the collimated light to the receiving surface.

28. The optical system of claim 27 wherein the collimator comprises a paraboloid of revolution.

29. The optical system of claim 26 wherein the stop comprises an anamorphic asphere.

30. The optical system of claim 26 wherein the receiving surface includes a layer of urethane material disposed between the receiving surface and the print.

31. The optical system of claim 26 wherein the volume of material is transparent to at least visible light.

32. The optical system of claim 31 wherein the volume of material is transparent to at least a wavelength of about 534 nanometers.

33. The optical system of claim 26 wherein the volume of material comprises a plastic.

34. The optical system of claim 33 wherein the plastic comprises an acrylic.

35. The optical system of claim 34 wherein the acrylic comprises methyl methacrylate.

36. The optical system of claim 26 wherein the volume of material that lies between the object and the focused image of the object is less than or equal to about 35 millimeters in a direction that is perpendicular to the receiving surface..

37. The optical system of claim 26 wherein the first reflecting surface comprises a paraboloid of revolution.

38. The optical system of claim 26 wherein the second reflecting surface comprises a hyperboloid of revolution.

39. The optical system of claim 27 further comprising a source for providing light to the collimator.

40. The optical system of claim 39 further comprising a detector for receiving the focused image and the collimated light from the refracting surface.

41. The optical system of claim 26 wherein the refracting surface comprises an anamorphic asphere.

42. The optical system of claim 1 wherein the stop comprises a field stop for the illumination path and an aperture stop for the imaging path.

43. The optical system of claim 15 wherein the stop comprises a field stop for the illumination path and an aperture stop for the imaging path.

44. The optical system of claim 26 wherein the stop comprises a field stop for the illumination path and an aperture stop for the imaging path.

45. The optical system of claim 1 wherein the imaging path is a subset of the illumination path.

46. The optical system of claim 15 wherein the imaging path is a subset of the illumination path.

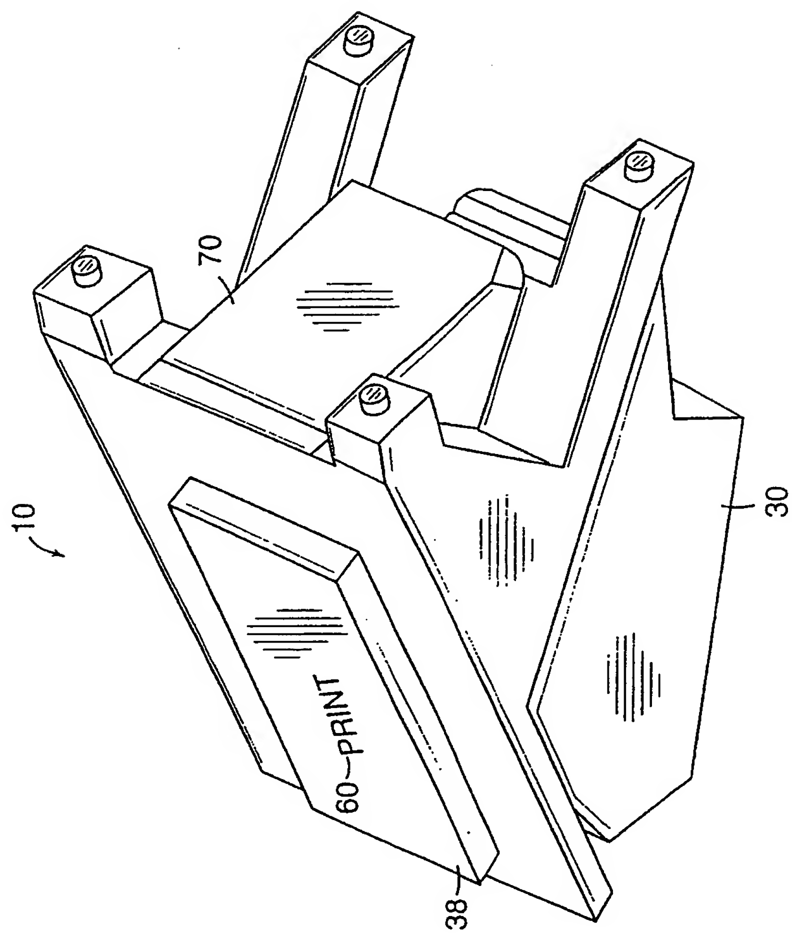
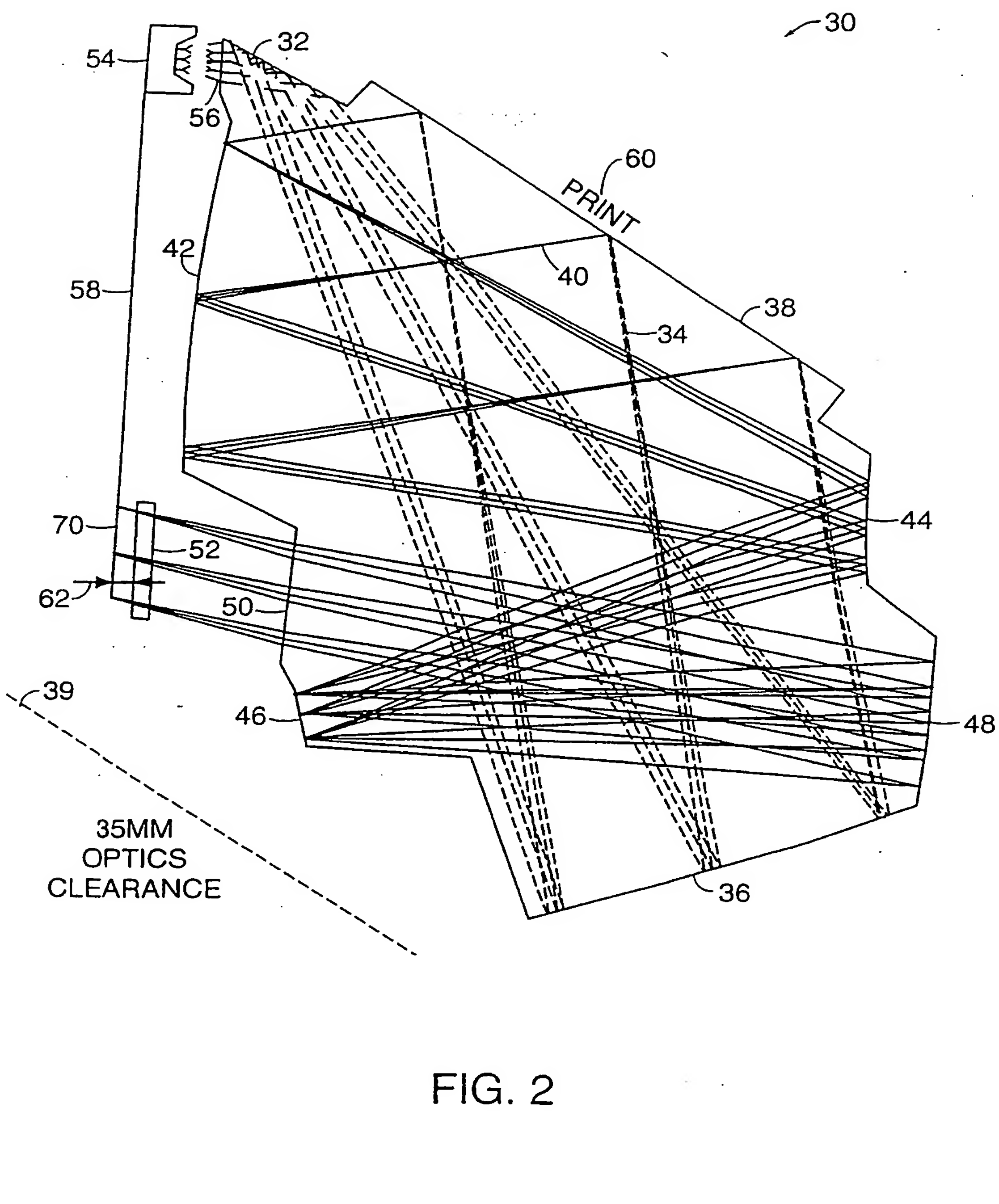


FIG. 1


30
32
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56
60
PRINT
42
40
58
38
34
44
70
52
62
50
39
46
48
35MM
OPTICS
CLEARANCE
36

FIG. 2

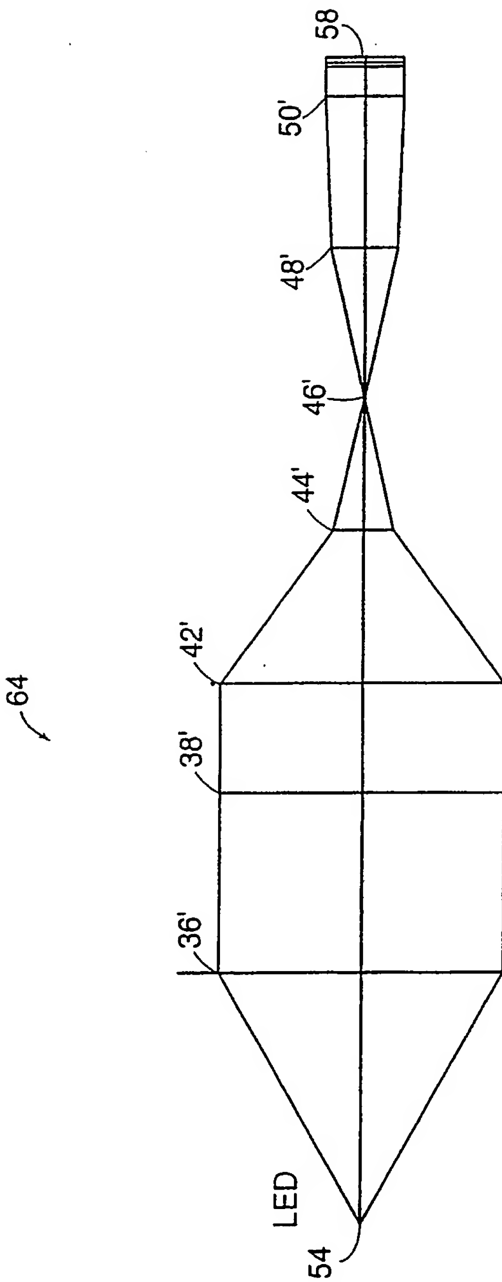

FIG. 3

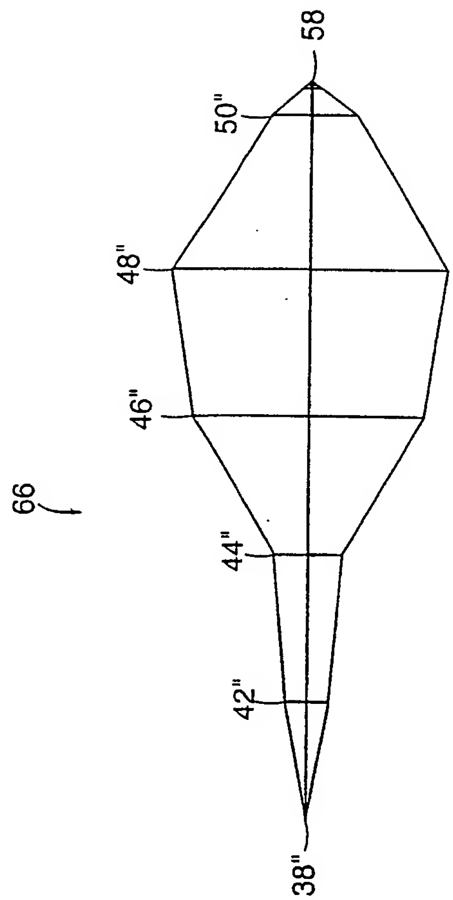

FIG. 4

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/04315

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G02B17/08 G06K9/20 A61B5/117

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G06K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A X	US 5 596 454 A (HEBERT RAY) 21 January 1997 see column 9, line 66 - column 10, line 34; figures 11,12 see column 7, line 25 - line 61	1,26 15, 18-23,25
A	EP 0 730 169 A (CANON KK) 4 September 1996 see abstract	1,15,26
A	US 5 309 276 A (RODGERS JOHN M) 3 May 1994 see abstract	1,15,26

[ ] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
20 October 1998	28/10/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Sonius, M

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 98/04315

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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